Functional Dart-Throwing Motion: A Clinical Comparison of Four-Corner Fusion to Radioscapholunate Fusion Using Inertial Motion Capture

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Abstract

Background Dart-throwing motion (DTM) is an important functional arc of the wrist from radial extension to ulna flexion. An aim of partial fusion surgery of the wrist is to maintain maximal functional motion while addressing the pathology. The radioscapholunate (RSL) fusion, accompanied with partial resection of the distal scaphoid, is thought to allow better DTM than other partial wrist fusions such as the four-corner fusion (4CF).

Question Does an RSL fusion allow better functional DTM than 4CF, and how does this range compare with healthy wrists and the patient's contralateral wrist?

Patients and Methods Patients who have undergone an RSL fusion or 4CF at our tertiary center were identified and invited to present to have their DTM arc measured. To accurately measure DTM, a previously validated inertial measurement device was used. Patient's functional DTM arc was measured in both unrestrained (elbow and shoulder free to move) and restrained (elbow and shoulder immobilized) fashions. This was compared with their contralateral wrist and a group of healthy control volunteers.

Results Overall five RSL fusions, 10 4CF and 24 control patients were enrolled in the study. There was no significant difference between functional DTM when 4CF and RSL fusion were compared. Both had significantly reduced functional DTM arc than control patients. There was no significant difference between the operated wrist compared with the patient's contralateral unoperated wrist.

Conclusion RSL fusion is not significantly better at maintaining functional DTM when compared with 4CF. Both surgeries result in decreased functional DTM arc when compared with control patients. This is a cohort study and reflects a level of evidence IV.

Level of Evidence This is a Leve IV, cohort study.

Keywords
- wrist
- dart-throwing motion
- radioscapholunate fusion
- four-corner fusion

Dart-throwing motion (DTM),[1] is a unique multiplanar movement of the wrist from radial extension to ulna flexion. It is commonly used for functional activities, such as hammering and pouring,[2] and may have provided an evolutionary advantage by allowing precision use of tools.[3,4]

DTM involves movement at the midcarpal joint and radiocarpal joint. The distal row moves as one segment. The axis of this carpal row appears to be 45 degrees pronated in the coronal plane when compared with the plane of the radius. This is due to the shape of the trapezoid, with its trapezoidal

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shape placing the trapezium in a more volar position, rotating the midcarpal motion plane in line with the dart-throwing axis.[5] During DTM, the proximal row allows some toggle movement to accommodate the distal row.[3] The center of rotation is thought to be in the lunate-capitate articulation.[3] Notably, little motion is noted at the scapholunate articulation.[6] The ligaments that allow this unique movement are the scaphocapitate and scaphoid-trapezium-trapezoid ligaments.[6]

Pathology within the carpal bones most commonly arises from scaphoid nonunion or scapholunate dissociation. Once secondary arthritis has evolved common treatment modalities include limited fusions or proximal row carpectomy.[7] Options for limited fusions depend on the stage of the arthritis, but include a four-corner fusion (4CF), being the excision of the scaphoid and fusion of the mid carpal joints, or the radioscapholunate fusion (RSL) and partial resection of the distal scaphoid which preserves the midcarpal joint.[8] Proponents of the RSL procedure hypothesize that preservation of the midcarpal will result in improved DTM and hence improved functional range of motion. This has been supported by cadaveric studies which show improved DTM post RSL fusion compared with 4CF and proximal row carpectomy.[9]

Measuring DTM is difficult. Its specific three-dimensional (3D) path makes clinical measurement inaccurate. Multiple modalities have been used to measure DTM but to be applicable to everyday use the method of measurement is required to be cost effective, portable, and safe. Methods previously tried include 3D imaging such as computer tomography,[3,5,10] surface markers,[11] and goniometers.[6,12] The 3D motion analysis has also been attempted.[13] These modalities can be expensive and can require radiation exposure that limits their feasibility in everyday assessment. We have previously presented a unique way of measuring DTM using inertial motion goniometer wrist devices.[14]

The aim of this study was to compare DTM in control patients to RSL or 4CF. Our hypothesis is that RSL will result in greater DTM compared with 4CF and both will have significantly less motion than the control group.

Patients and Methods

Study Design

This study is a prospective observational evaluation of patients who had previously undergone an RSL fusion or 4CF compared with a set of healthy control volunteers.

Participants and Exclusion Criteria

The study was approved by the hospitals' Human Research and Ethics Committee (HREC 14/88 October 2015). All patients that underwent a partial wrist fusion between the years of 2007 and 2012 under a single surgeon in a large tertiary center were included in the trial. A search of the surgical database revealed 8 patients that had undergone a RSL fusion and 19 patients that had undergone 4CF. All patients were contacted. Five patients from the RSL group (63%) and 10 patients (52%) from the 4CF group were able to be examined and their range of motion measured. Patients were at least 36 months post index surgery. Indication for surgery can be found in ►**Table 1**.

Table 1 Patient characteristics

Characteristic	Controls	RSL	4CF
Number of volunteers	24	5	10
Male:female	9:15	2:3	6:4
Age Mean (range)	34.8 (21–55)	55.6 (23–68)	64.2 (45–77)
Hand dominance R:L	22:2	5:0	9:1
Occupation	11 nurses, 6 doctors, 3 physio, 3 other		
Pathology	Nil	Posttraumatic OA (4), RA (1)	SLAC, (8) SNAC, (2)
Time since surgery	Nil	Average: 80.2 months Range: 67–95 months	Average: 43.8 months Range: 32–77 months

Abbreviations: 4CF, four-corner fusion; L, left; OA, osteoarthritis; R, right; RA, rheumatoid arthritis; RSL, radioscapholunate; SLAC, scapholunate advanced collapse; SNAC, scaphoid nonunion advanced collapse.

For the control patients, volunteers were recruited from within the hospital via flyers. Previous wrist injury or surgery was an exclusion. Twenty-four volunteers were subsequently examined and their wrist DTM recorded in a similar fashion to the operative patients.

Sample Size

Sample size was limited by the number of volunteers and patients were able to present for the wrist measurements. Overall three sessions of 2 hours were set aside to gather volunteers. All volunteers who met the inclusion criteria were recruited.

Surgical Technique

Surgery was undertaken by the senior author (R.S.P.) under combined regional anesthesia and general anesthetic with arm-based tourniquet control, the patient supine on a radiolucent hand table. Intravenous antibiotics were given on induction.

A universal dorsal approach was used for all cases via the three-fourths extensor interval and a Z-plasty flap made of the extensor retinaculum to aid with closure over fixation implants and extensors tendons at the end of the case, with a neurectomy to the posterior interosseous nerve. The dorsal carpus was exposed via raising a Berger's capsular flap.[15]

Radioscapholunate Fusion

An extended radial-based Berger's dorsal capsular flap[15] was elevated to expose the intercarpal spaces and confirm the integrity of the midcarpal articulation. Both the dorsal radial tubercle and the distal one quarter of the scaphoid were excised to allow positioning of the dorsal plates and to free up the intercalated segment respectively, the bone was later used for grafting. The distal radius, proximal lunate, and scaphoid were prepared with osteotomes, curettes and a 3-mm high-speed burr with intermittent saline irrigation for heat minimization. Once fresh bone surfaces were match for maximum congruency, the scaphoid and lunate were positioned in an "open-fusion" position with the scapholunate space maintained to maintain the midcarpal articular congruency. Position was held with temporary Kirschner's wires (K-wires) and the alignment check in both planes under image intensification (II). Fixation was obtained using an extra-articular radial plate as shown in ►**Fig. 1A** or 2.4-mm locking plates oblique and short T-plates (De Puy Synthes, West Chester, PA), with a minimum of two screws in each of the scaphoid and lunate. Local bone graft was applied to the dorsal aspect of the carpus or radiocarpal spaces and finally checked on II to ensure no joint impingement. The dorsal Berger flap[15] was closed over the plates and retinacular closure with 4/0 polydioxanone (PDS) suture to cover the extensor tendons, followed by 2/0 vicryl and 3/0 Monocryl to skin. A dry absorbent dressing applied and finally a volar plaster slab (2 weeks) followed by a fiberglass cast (4 weeks). A sample of postoperative radiographs can be found in ►**Fig. 1B**.

Four-Corner Fusion

The surgical set up and dorsal approach used as described above; however, a limited radial styloidectomy and full scaphoidectomy were undertaken, the bone used later for grafting. The four-corner point intercarpal spaces were prepared in a similar fashion to above and bone graft applied and reamed into place. Temporary K-wire fixation with II control and fixation achieved with a PEEK Fusion Cup (Tri Med, Valencia, CA) and titanium screws, again with care to ensure at least two locking screws in each carpal bone and no penetration into the radiocarpal joint space. Closure and initial immobilization were as described above, followed by a removable splint and hand therapy. A sample of postoperative radiographs can be found in ►**Fig. 2**.

Outcomes Measured

The primary outcome measured was DTM in degrees. Secondary outcomes included flexion and extension range in degrees.

Fig. 2 Radiographs of four-corner fusion, using a radiolucent contoured circular dorsal plate following scapholunate advanced collapse of the wrist.

The computer algorithm broke down the dart throwers motion into a flexion and extension arc. Giving the maximum range of flexion/extension and radial–ulna deviation during the DTM. To obtain a combined arc representing the arc of DTM, Pythagoras' Theorem was used, combining the flexion/extension and radial–ulna arcs to produce a right-angled triangle, and labeling the hypotenuse as the functional DTM arc (►**Fig. 3**).

Measurement Method

To measure functional DTM, an inertial measurement device was utilized.[16] These devices consist of a triaxial accelerometer, gyroscope, and magnetometer. They are affordable, portable, and accurate. They are small and light enough to allow measurement in real time, without limiting the speed or range of motion of the wrist.[17] Their portability also ensured that they were able to be used in an office or practice setting, increasing convenience for the patient, and practitioner.

Their use in measuring functional DTM has previously been evaluated and validated in a small pilot study preceding this study.[16]

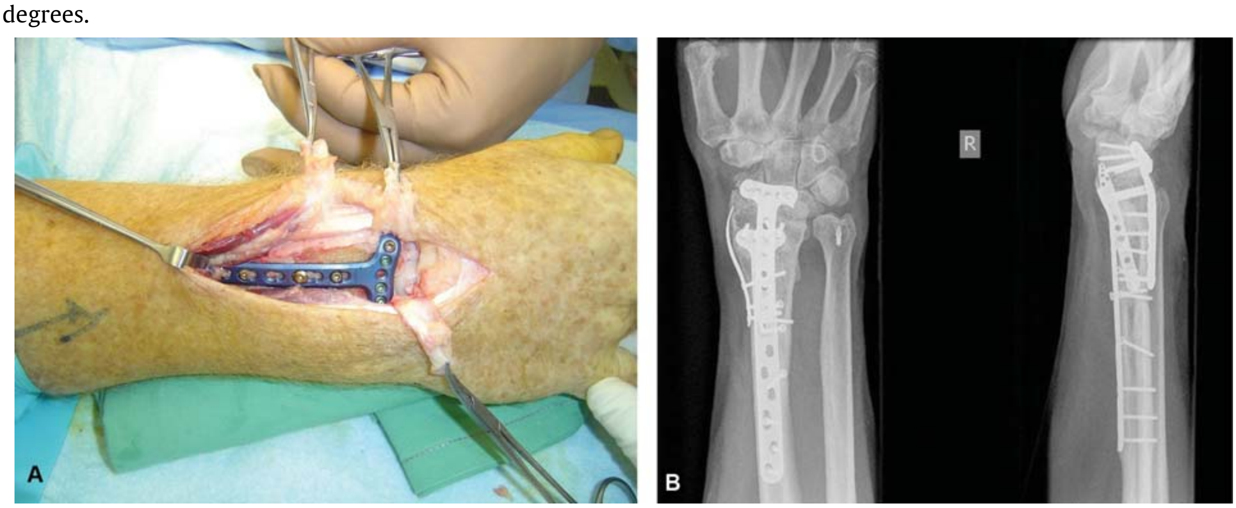

Fig. 1 (A) Intraoperative image of RSL fusion and spanning locking plate in situ in a patient suffering from posttraumatic arthritis and (B) postoperative radiographs demonstrating RSL fusion. (B) Radiographs of RSL fusion, undertaken for early posttraumatic arthritis following fixation for intraarticular distal radial fracture. RSL, radioscapholunate.

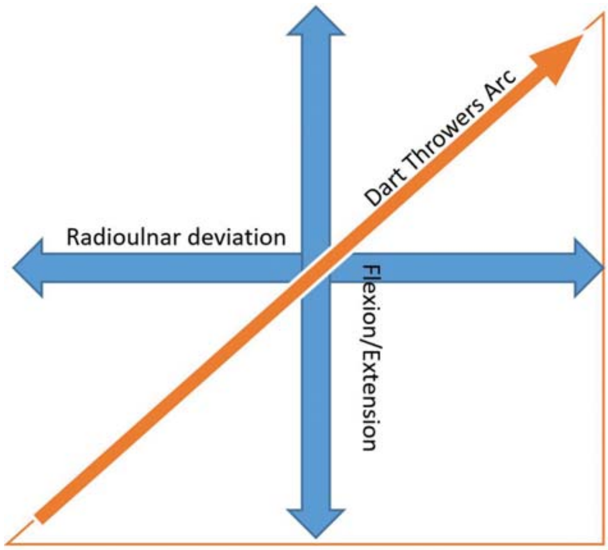

Fig. 3 Pythagoras theorem used to find DTM range of motion from measured flexion/extension and radio-ulnar deviation arcs. DTM, dart-throwing motion.

Two sensors were used to collect data. The first was placed on the dorsum of the hand and the second was placed on the forearm of the patient (►**Fig. 4**). The sensors were held tight with Velcro straps, reinforced with tape as previously described.[14]

Measurement of functional DTM was undertaken in the following manner. Initially the sensors were calibrated for each individual by measuring maximum radial and ulna deviation and flexion and extension of each wrist three times.

DTM was evaluated in two ways. Initially it was evaluated in real time, in a functional manner, with the patient being asked to physically throw a dart at a dart board as naturally as they could (►**Fig. 5**). This was repeated three times. Subsequently the patient was asked to throw the dart once more, but this time with the forearm restrained, with the aim being to restrict movement from other joints and hence isolating carpal motion as best possible. The patient was seated at a table and a block was used to hold the arm at 45 degrees to the table (►**Fig. 6**). The angle of the base of the block and forearm rotation was stationed to suit the participant's natural dart-throwing angle. With the forearm firmly restrained, the participant was once again asked to throw the dart at the dart-board, and the range of motion at the wrist was measured. All measurements where undertaken three times for both wrists.

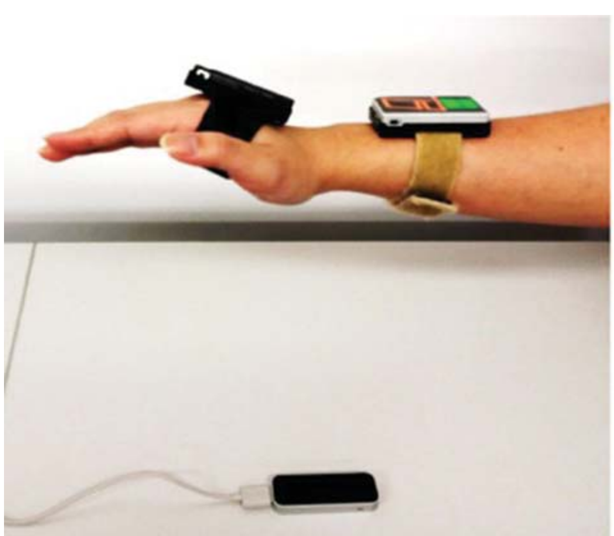

Fig. 4 Inertial measurement device probes placed on hand and forearm.

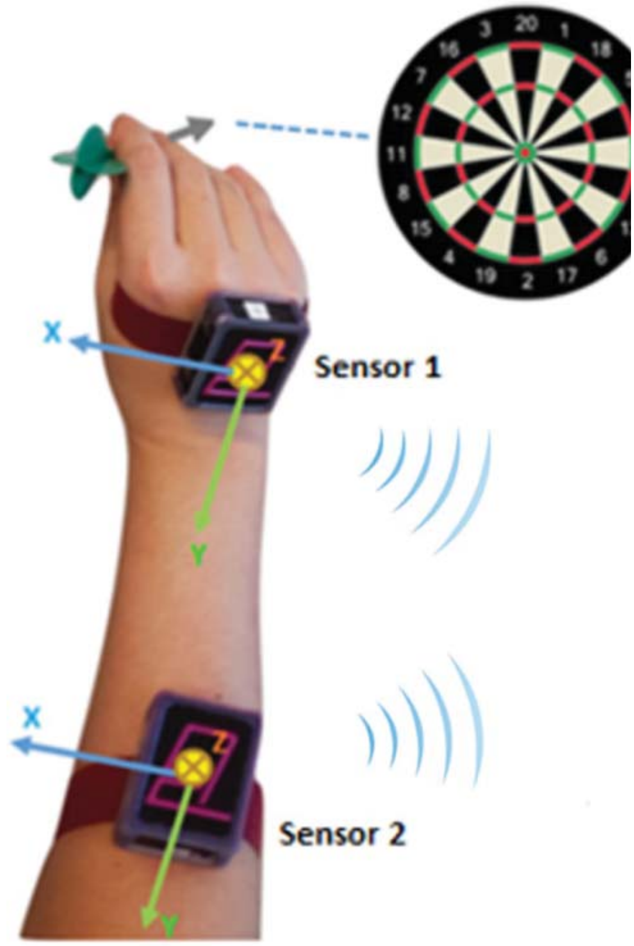

Fig. 5 Unrestrained dart-throwing motion measured by asking the patient to throw a dart at a dart board.

Data Collection

Data collected included participant age, dominant hand, occupation, and past medical history in regard to wrist injury or surgery. Measurement data collected included maximum range of motion in flexion/extension and ulnar/radial deviation, and subsequent range of motion in the flexion/extension and radioulnar plane was measured during free and restricted DTM. All measurements were taken three times on both wrists. Baseline demographics can be found in ►**Table 1**.

Statistical Analysis

Data were tested using the Shapiro–Wilk test to first demonstrate normal distribution and subsequently mean and

Fig. 6 Restrained dart-throwing motion measured by immobilizing elbow and shoulder using a custom made block.

standard deviation was used to measure range of motion in degrees. Mixed datasets were analyzed using the one-way analysis of variance to determine statistically significant differences between groups with $p < 0.05$ defining significance. Categorical data were analyzed using the Chi-square test.

Results

Standard Range of Motion

The standard range of motion was compared between control patients and postoperative patients. Results can be found in ►**Table 2**.

As expected range of motion was greater in the control group ($p < 0.001$). The arc of motion in either plane of the RSL group was not significantly different to that of the 4CF group.

A comparison was also made between the dominant hand versus the nondominant hand in the control group, results can be found in ►**Table 3**. There was no significant difference in ROM in regards to hand dominance.

Table 2 Range of motion results comparing RSL, 4CF, and control patients

	RSL In degrees (SD)	4CF (SD)	Control (SD)	*p*-Value
Flexion/extension	61.4 (16)	53.4 (19)	136.1 (35)	Control vs. RSL: <0.001 Control vs. 4CF: <0.001 4CF vs. RSL: 0.651
Radial/Ulnar deviation	37.8 (24)	33.4 (16)	61.9 (48)	Control vs. RSL: 0.005 Control vs. 4CF: 0.005 4CF vs. RSL: 0.113

Abbreviations: 4CF, four-corner fusion; RSL, radioscapholunate; SD, standard deviation.

Table 3 Comparison of range of motion between the dominant and nondominant hand of control patients

	Dominant hand	Nondominant hand	*p*-Value
Flexion/extension	135.7 (24)	136.4 (43)	0.945
RUD	64.4 (61)	59.5 (30)	0.723

Abbreviation: RUD, radial/ulnar deviation.

In the postsurgical group, a comparison was made between the operated wrist and the nonoperated wrist (►**Table 4**).

As expected, the operated wrist was more restricted than the nonoperated wrist; however, this difference was not statistically significant" to the end of the sentence. Also the nonoperated wrist in surgical patients was stiffer than the control group with the average arc of motion close to half that of control patient in both planes (►**Table 2**).

Finally, a comparison was made between preoperative ROM of the operated hand and the postoperative ROM, assessing average change in the flexion/extension arc from preoperative values (►**Table 5**). It is noted that RSL fusion tended to increase range of motion however 4CF tended to decrease ROM; however, this did not reach significance.

Dart Thrower's Range of Motion

Subsequently functional DTM was assessed in both the control group and the postoperative group. Results can be

Table 4 Comparison of range of motion between the operated and nonoperated wrists

	Operated side	Nonoperated side	*p*-Value
RSL: flexion/extension	61.4 (16)	67.2 (35)	0.748
RSL: RUD	37.8 (24)	42.8 (26)	0.759
4CF: flexion/extension	53.4(19)	77.3 (37)	0.089
4CF: RUD	33.4 (16)	62.3 (60)	0.156

Abbreviations: 4CF, four-corner fusion; RSL, radioscapholunate; RUD, radial/ulnar deviation.

Table 5 Change in flexion extension arc from preoperative values versus type of surgery performed

	RSL	4CF	*p*-Value
Change in flexion/extension arc from preoperative values	13.1 (23)	−20.5 (34)	0.073

Abbreviations: 4CF, four-corner fusion; RSL, radioscapholunate.

Table 6 Comparison of DTM between groups

	RSL	4CF	Control	*p*-Value
DTM unrestricted	58.8 (19)	88 (48)	108.2(53)	0.085
DTM restricted	31.3 (11)	34.6 (37)	77.8 (36)	0.001

Abbreviations: 4CF, four-corner fusion; DTM, dart-throwing motion; RSL, radioscapholunate.

found in ►**Table 6**. Of note both operative groups had a reduced arc of functional DTM compared with the control group; however, this was only significant in the restricted DTM. Notably there was no difference in DTM between RSL and 4CF group either in unrestricted ($p = 0.222$, ►**Fig. 7A**) or restricted ($p = 0.888$, ►**Fig. 7B**).

Discussion

The RSL fusion is thought to improve DTM compared with other types of partial fusion, as it maintains the midcarpal joint. However no study has directly compared these cohorts of patients. This study suggests there is no difference in the postoperative functional DTM arc after 4CF or RSL fusion. The 4CF cohort appears to have a slight advantage in maintaining the functional DTM arc compared with RSL fusion, although this was not significant. It is noted that both operations have significantly reduced range of motion compared with a control population. A further finding was that compared with their nonoperated wrist, the operated wrist does not have a significantly different range of motion; either in flexion/extension, radio/ulnar deviation, or DTM. This is the first study to directly compare these two operations and to a control.

Limitations and Strengths

Limitations of our study include the small number of patients that could be tested, as these operations, especially the RSL are uncommon, even in a tertiary hospital. Also, patients were at different time points postoperatively and there was a slight age difference between cohorts, with the RSL patient being generally younger. This may be attributed to the underlying pathology resulting in surgery, with the RSL group predominantly suffering from posttraumatic arthritis compared with the 4CF group who suffered mostly from a scapholunate advanced collapse (SLAC) wrist. Another limitation is that although we believe we measured functional DTM, we cannot fully ascertain whether this movement occurred purely from carpal motion as this may only be possible through more invasive radiological modalities. However we attempted to reduce motion from other joints by immobilizing the shoulder, elbow, and forearm using a custom block.

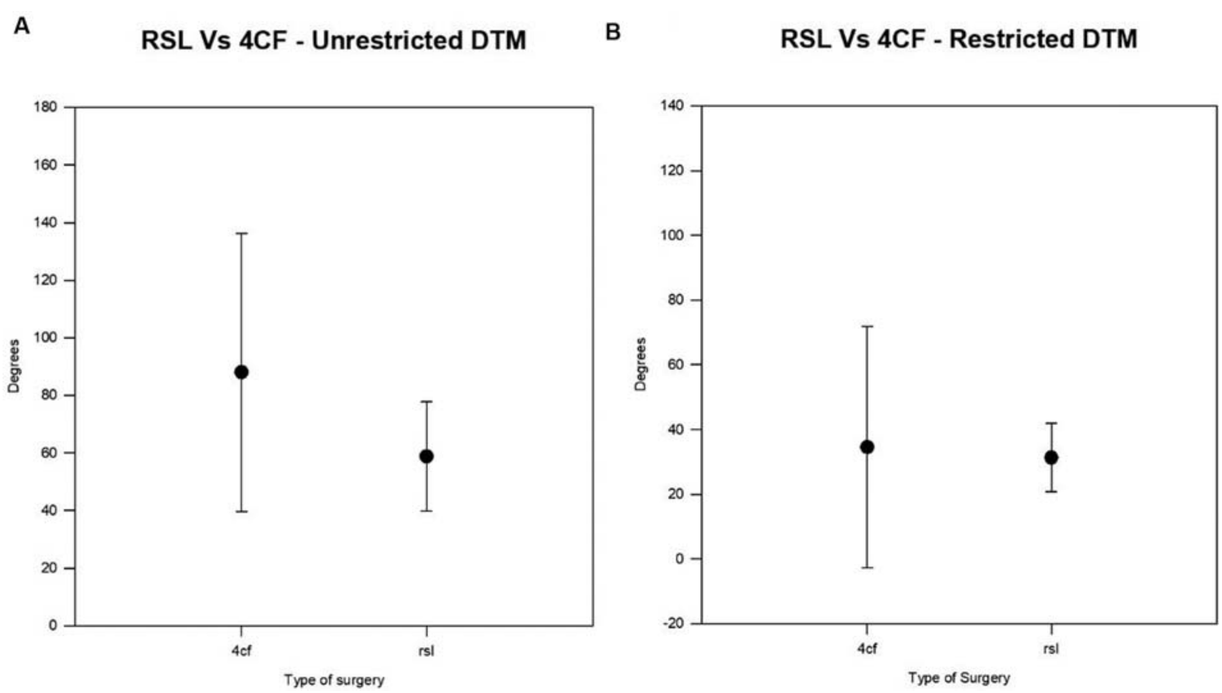

Fig. 7 (**A**) Comparison of unrestricted dart throwers motion range between patients undergoing RSL fusion (RSL) versus four-corner fusion (4CF). (**B**) Comparison of restricted dart-throwers motion range between patients undergoing RSL fusion versus 4CF.

Our study found that functional DTM motion in RSL fused wrists was limited to approximately 50% compared with healthy control patients. Rust et al[9] recently conducted a cadaveric study assessing range of motion between RSL, 4CF, and proximal row carpectomy. They used a goniometer to measure the DTM using the Bugden method.[6] They found that after RSL fusion 74% of DTM was maintained, compared with 4CF where radial-extension decreased to 53% and ulnar-flexion to 84% of the control motion. They suggested that DTM was better maintained in the RSL fusion group. Their study had limitations, including using cadavers with limited wrist pathology and assessing range of motion using tendon pulleys. Calfee et al[18] performed another cadaveric study assessing range of motion in cadavers undergoing RSL fusion. They found that flexion/extension and radial/ulnar deviation was reduced but motion was maximally maintained in the DTM arc.

Several factors may help explain our results. Namely, we noted a global decrease in ROM in all planes in both the operated and nonoperated wrist. In fact, the operated wrist was not significantly stiffer than the nonoperated wrist. It may be that the functional DTM, that is, the action of physically throwing a dart, may not be equivalent to the maximal DTM that can be measured in a cadaver. Also the contralateral side were not radiographed, hence it is difficult to ascertain whether those wrists may be suffering from disease, albeit asymptomatic.

Conclusion

In conclusion, our hypothesis that RSL fusion would result in improved functional DTM compared with 4CF was not supported by our results. The choice of salvage procedure should not solely be based on the aim to preserve DTM but to treat the underlying pathoanatomy, fusing affected joints.

Note

The work was performed at University Hospital Geelong.

Ethical Approval

This study has been approved by our institutions Ethics Board.

Conflict of Interest

None declared.

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